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# Role of renewable energy in China's energy security and climate change mitigation: An index decomposition analysis

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ABSTRACT

Renewable energy is an efficient tool to support China's endeavors to keep energy independence and mitigate climate change. This paper applies a Divisia index approach to investigate the factors governing renewable energy development in China, including the supply mix, energy security, carbon emission, and to forecast these requirements for the year 2020 and 2030. Grey relational model is employed to verify the relationships between renewable energy and its drivers. The results of the forecasts reveal the challenges of long-term deployment for renewable energy technologies. Other results show that during the research period, energy security makes a major contribution to renewable energy development. Energy security and substitution rate have relatively closer relationships with new and total renewable energy consumption respectively than that of other factors. Scenario analyses suggest that strong and continuing renewable energy policies will be helpful to achieve sustainable energy development in China and a strong synergy between renewable energy and energy security would emerge in the future.

## 1. Introduction

### 1.1. Renewable energy and its role in sustainable development

Renewable energy development could be an efficient and practicable path to achieving the sustainable development. With the rapid deployment of renewable energy technologies, renewable energy is not only taken as a sustainable choice of clean energy system, but also as an approach to addressing other social pressing needs, including improving energy security [1], reducing environmental impacts associated with fossil fuel consumption [2], as well as mitigating climate change [3]. In 2016, there were at least 176 countries in their efforts to setting renewable energy goals, and renewables have accounted for an estimated 30% of the installed capacity and 24.5% of the electricity supply at the global level. Given the huge technical and economic potential of renewable energy, it is reasonable to expect a golden opportunity for renewable energy in the future global energy mix.

Provided that a secure, sufficient and reliable supply of energy is very crucial for the sustainability of modern societies, renewables can efficiently address energy security issues extending to both supply and demand side. On the supply side, due to the scarcity and exhaustibility of fossil energy, renewables will play an increasingly significant role in meeting the huge energy demand. IPCC suggested that 2.5% of renewable potential will meet 80% world energy demand in 2050 [4]. On the demand side, with the characteristics of sustainability and environmental-friendly, renewables could solve the security of energy use. Some scholars discussed energy security issues from the aspects of energy supply and energy use and concluded the role of renewables in energy use security [1]. The emerging symbiosis of renewable energy development and energy security has been analyzed in [5] by examining the evolution of energy security concept and verifying the deep symbiosis.

Renewable energy could also bring environmental benefits and other social benefits, such as increasing educational opportunities and jobs, reducing energy poverty and gender inequality [6,7]. Compared with the use of fossil fuels, renewable energy consumption would generate much fewer carbon emissions and environmental pollutants, which helps to mitigate climate change and curb environmental pollution [8,9]. With numerous regions seeking the transition to renewable energy, the employment numbers in renewable energy industry have

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reached 9.8 million in 2016, a growth of 1.1% over 2015 [2]. Lastly, when access to modern energy services is the marrow of sustainable development, distributed renewable energy technologies provide unprecedented opportunities for alleviating energy poverty in remote and rural areas [10].

### 1.2. Energy security, climate change and economic development in China

Since China was a net import country of crude oil in 1996, energy supply risk aversion has been included in national energy security strategy. In 2009, China, for the first time, translated into a net importer of coal, and the dependency of oil import was about 53% [11]. In 2013, the proportion of oil import and natural gas import reached 58.9% and 27.6%, respectively [12]. Energy security concerns along with energy structure adjustment are pressing tasks in China. In addition, the dominance of coal in energy structure results in the vast quantities of greenhouse gas and other pollutants, which is the major cause for dire environmental dilemmas. Traditional use of biomass for cooking and the low quality of electricity supply in remote and rural areas also create a barrier to poverty alleviation in these areas. In this case, energy security will be an important challenge to future sustainable development in China and renewable energy development may be valuable to address this issue.

As a developing country, China has implemented a dozens of policies and adopted voluntary emission reduction targets to cope with climate change. The National Development and Reform Commission (NDRC) of China issued the annual report of China's Policies and Actions for Addressing Climate Change since 2008 [13]. The national plan for coping with climate change (2014–2020) has been released in November 2014, which identified the principles, goals, pathways, and policy directions in a bid to address climate change [14]. Based on the U.S.-China Joint Announcement on Climate Change, China has intended to approach carbon emission peak around the year 2030. China's Intended Nationally Determined Contributions polished in year-end 2015 demonstrated that China is responsible in coping with climate change and renewable energy development will be a key part in China's low-carbon energy system.

With a rapid economic development in China within the last three decades, Chinese economy has entered a new era, namely the “New Normal” [15]. This new stage will not only become the hallmarks to be engraved in history, but also depict the direction of future economic development in three aspects: medium-to-high speed growth, on-going economic restructuring and innovation-driven development pattern. The Twelfth Five-Year Plan for National Strategic Emerging Industries Development has outlined renewable energy industry as one of the key strategic emerging industries [16]. This is to say that renewable energy will become the new source of economic growth in China.

### 1.3. China's energy sector: The need for renewable energy development

#### 1.3.1. Primary energy sector

China is the world's largest energy producer and energy consumer in 2014. Fig. 1 shows the primary energy production and consumption in China [17]. The first obvious result is the dominant role of coal in China's energy structure and an increasing imbalance between production and consumption. This situation is the major cause of environmental pollution and greenhouse gas emissions. Second, renewable energy and nuclear power become an increasingly important part in energy structure, which correspond to the rapid growth of renewable energy utilization. As suggested by [13], China's renewable energy capacity contributed about 24% of the world total, and its additional renewable energy capacity represented about 37% of the world total additional capacity in 2013. Third, with the excess of energy consumption over energy production, the proportion of crude oil in the picture indicates that the security of oil import will be a major challenge in the near future.

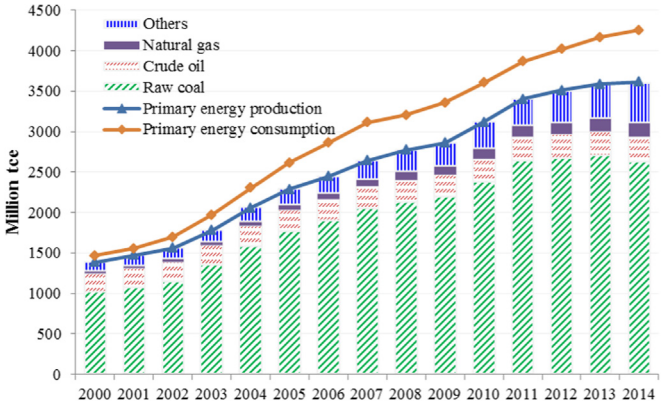


**Fig. 1.** Primary energy production and consumption in China (1980–2014). Note: Others include hydropower, nuclear power and other renewable energies.

#### 1.3.2. Electricity sector

From 1993 to 2013, electricity demand growth averaged 9.31% while GDP has grown at an average rate of 14.36% [18]. One factor contributing to such a growth includes the rural electrification program, which helps to the wide application of electricity in rural areas. Fig. 2 depicts the electricity generation in past two decades. The dominant role of coal in energy system reflects the major role of thermal power in power mix. Electricity generation from other technologies has a slightly larger growth than that from thermal power, which is 10.14% and 9.12%, respectively. At the same time, the government has closed the outdated thermal power capacities. For example, China retired 4.47 GW of small thermal power units and more than 1000 small coal mines in 2013 [13]. In this regard, the efficiency of electricity generation has improved in recent years.

#### 1.3.3. Renewable energy system

From a global perspective, China has taken a leading role in international renewable energy market, such as hydropower capacity, wind power capacity, solar photovoltaic capacity as well as different kinds of renewable energy generations [2]. This fact coincides with the large investment in China's renewable system and the ambitious renewable energy program, including the development plan for marine renewable energy over the period 2013–2016 [19] and other renewable policies stated in below. However, the share of renewable energy in China's energy structure should be further boosted because of the small proportion of renewables in energy consumption.

Hydropower, including small hydropower plants, is the most important renewable energy source in China. This significance supports the electricity demand and helps to tackle energy poverty issues in Southwest China [20]. Hydropower plants are generally located in Yangtze River, and Southwest China (Yunnan, Sichuan, Guizhou) is the

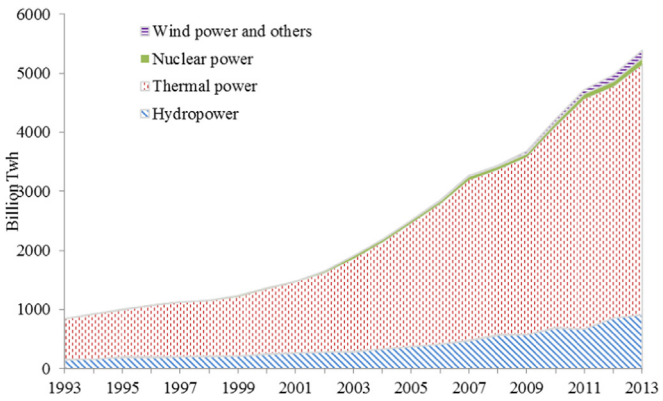


**Fig. 2.** Electricity generation in China (1993–2013).

major basin for hydropower generation. According to the report of NDRC [13], some large-scale hydropower plants, such as the Xiluodu and Xiangjiaba projects, were in operation in 2014, a year earlier than the target date in the Twelfth Five-Year Plan for energy development.

Before the 21 century, the proportion of wind power in energy mix was negligible. However, it has experienced a unpredictable growth since 2005 and it is the first time for wind power to be the third source for electricity generation, which exceeded nuclear power generation in 2012 [18]. Besides the supported policies regarding the extension on the coverage of wind power projects, the feed-in tariff policy for offshore wind power has been issued by NDRC in 2014. The Notice on Carrying out Demonstration Projects on Biomass Fuel Boilers will be beneficial to the construction of 120 demonstration projects nationwide in order to achieve higher penetration level of biomass energy.

#### 1.3.4. Renewable energy policies in China

In 2016, China has been meeting 62% of its energy demand by coal sector. However, increasing concerns about the environmental impacts of coal consumption have prompted a shift in national energy policy. Since 2005, renewable energy development is one important subject of China's energy policies. To succeed promotion programs of renewable energy (RE) development, a series of regulatory policies, fiscal incentives, and case demonstration plans have been enacted for different kinds of renewable technologies in China [21]. For regulatory policies, following by Renewable Energy Law of the People's Republic of China in 2005, the mid and long term development plan of renewable energy has also issued by National Energy Administration in 2007. Fiscal incentives are mainly practiced through an electricity surcharge. The international experience of renewable energy fiscal reform could suggest possible paths to promote wide application of renewables in China [22]. The first panel of 81 new energy demonstration cities has been chosen to example the possibility of high renewable penetration at city level. As one of the most commonly used support mechanism around the world, renewable portfolio standards has recently enacted by the National Energy Administration of China. Even though the 15 percent share of primary energy consumption from non-fossil fuel has discussed in China since 2009, it has been first introduced in government's document in September 2014 [23]. The present renewable policies are targeted on how to enhance the ongoing renewable electricity integration challenges.

Along with the increasing numbers of supporting policies, the expansion of renewables in China has surpassed all expectations. China has become the top country for both total renewable installed capacity and renewable electricity generation. [2]. China, the world's largest wind power installed and generation countries in 2016, is also the leader in the production of solar photovoltaic cells since 2010 [12] and renewable energy is increasingly being used to meet the heating demand in buildings. It is no exaggeration to say that China has overwhelmingly led the world in the non-fossil energy development [24]. According to the recent promise, China has planned to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030.

### 1.4. The aim of this paper

With the above background, renewable energy development, a vital part of sustainable development, associates with energy security [25], climate change mitigation and energy structure adjustment in Chinese context. Renewables could be the substitute for traditional electricity sources for energy supply security and become a clean energy source to cope with the energy use security and rural energy poverty [26]. Based on literature review, this paper applies Divisia index decomposition approach to assess past contributions of different factors to renewable energy consumption in China. For different economy growth cases, such requirements are forecasted for the year 2020, taking into account, the 15% renewable in China's energy mix and different carbon intensity reductions plans. Provided that there is a wide range of possibilities for long-term planning of high renewable penetration rates, the historical relationships between renewable energy development and its influencing factors have also been examined. A general description of the energy sector and energy policies is used to present the necessary background for energy transition to renewables. This paper intends to address the following issues:

(1) Based on the current situation of China's energy system, which factors contribute to renewable energy development in the past two decades?
(2) How do requirements for renewable energy consumption vary across different scenarios?
(3) What is the relationship between renewable energy development and its drivers, including energy security, climate change and technology innovation?

The reminder of this paper is structured as follows. Section 2 presents the methodology, data and scenarios to assess the evolvement of renewable energy consumption in China. The results discussions are shown in Section 3. Section 4 summaries the main conclusions and policy implications of this study. Finally, concluding remarks and suggested model improvements are also included in the last part of Section 4.

## 2. Methodologies

### 2.1. Conceptual framework for renewable energy decomposition analysis

As shown in Fig. 3, this paper applies index decomposition analysis – LMDI (Logarithmic Mean Divisia Index) type I [27] to evaluate past roles of different components to renewable energy generation and to

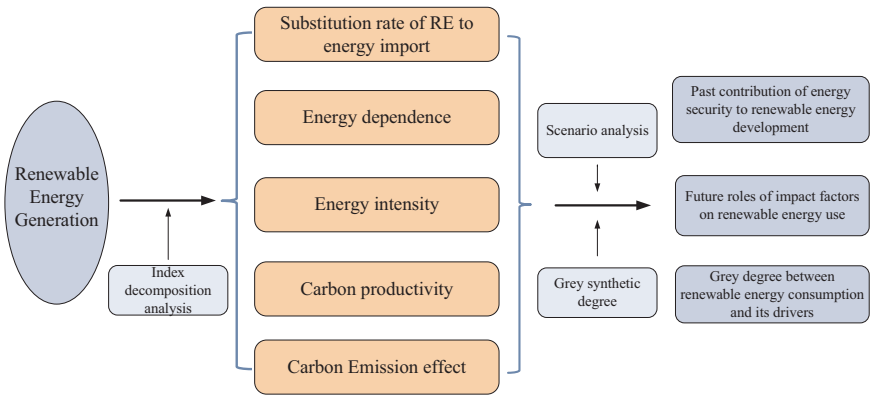
Renewable Energy Generation
Index decomposition analysis
Substitution rate of RE to energy import
Energy dependence
Energy intensity
Carbon productivity
Carbon Emission effect
Scenario analysis
Grey synthetic degree
Past contribution of energy security to renewable energy development
Future roles of impact factors on renewable energy use
Grey degree between renewable energy consumption and its drivers

**Fig. 3.** Conceptual framework of this paper.

forecast future paths for these contributions by scenario analysis. Grey synthetic degree is also used to untangle the relationships between renewable use and its driving forces. Lastly, based upon the analyses and discussions on the results, main conclusions and policy implications are obtained for the sustainable development of renewable energy system.

### 2.2. Decomposition method for renewable energy consumption in China

Divisia approach stems from the price index measurement on numerous research fields. Nowadays, two widely-used decomposition methods, namely the SDA (structural decomposition analysis) and IDA (index decomposition analysis) method, are generally applied in energy-related environmental analysis. A review on decomposition techniques suggested that the LMDI method was an appropriate means to research influencing factors [28]. The SDA method, featured by input-output analysis, was used to study the structure factors of energy consumption and energy-related $CO_2$ emissions [29].

However, the IDA method is also widely accepted by scholars from energy and environmental policy research [30–32]. Adaptive Weighted Divisia (AWD) was used to study the evolutionary mechanism of carbon intensity from residential end uses in 10 OECD countries and it is found that decreases in aggregate carbon intensity are neutralized by end-use structure changes toward more carbon-intensive activities for the studied countries [33]. The LMDI method is used to research the variations of China's industrial $CO_2$ emissions over the period 1998–2005 and the different contributions of impact factors to industrial $CO_2$ emissions were found [34]. A hybrid IDA model was proposed to research the energy consumption in Singapore residential sector and the proposed method is better than traditional IDA models in some aspects [35]. Similar research by Belakhdar et al. adopted this method to assess past contributions of different factors to renewable energy in Morocco and the results from 27 scenarios suggested that huge planning challenges in achieving a high renewable percentage target in Morocco [36]. Thus, the LMDI method is employed to identify the drivers behind the changes of renewable energy consumption in this research.

When the variables have been defined in Table 1, the LMDI method used in renewable energy decomposition could be expressed as Eq. (1).

$$Re = \frac{Re}{EIM} \times \frac{EIM}{E} \times \frac{E}{G} \times \frac{G}{C} \times C = SR \times ES \times EI \times CP \times CE \quad (1)$$

For a period [0, T], renewable energy decomposition by LMDI model could result in the total variations in Eq. (2) and individual contributions in Eqs. (3–7).

$$\Delta Re = Re_T - Re_0 = \Delta SR + \Delta ES + \Delta EI + \Delta CP + \Delta CE \quad (2)$$

$$\Delta SR = \frac{Re_T - Re_0}{\ln(Re_T/Re_0)} \times \ln(SR_T/SR_0) \quad (3)$$

$$\Delta ES = \frac{Re_T - Re_0}{\ln(Re_T/Re_0)} \times \ln(ES_T/ES_0) \quad (4)$$

**Table 1**
Definition of variables.

| Variables | Definition |
|---|---|
| RE | Renewable electricity generation |
| EIM | Energy import |
| E | Total energy consumption |
| G | Total Gross Domestic Product |
| C | Total carbon emission |
| SR | Substitution Rate of renewable energy to oil import |
| ES | Energy security or energy dependence |
| EI | Energy Intensity |
| CP | Carbon Productivity -Low carbon economy indicator |
| CE | Carbon emission effect |

$$\Delta EI = \frac{Re_T - Re_0}{\ln(Re_T/Re_0)} \times \ln(EI_T/EI_0) \quad (5)$$

$$\Delta CP = \frac{Re_T - Re_0}{\ln(Re_T/Re_0)} \times \ln(CP_T/CP_0) \quad (6)$$

$$\Delta CE = \frac{Re_T - Re_0}{\ln(Re_T/Re_0)} \times \ln(CE_T/CE_0) \quad (7)$$

With Eqs. (3)–(7), this paper decomposes the annual renewable energy consumption. As China has great potentials for renewable energy development, besides the increasing cost-competitiveness of renewable energy technologies, other main drivers for this shift are the social co-benefits of carbon emission reduction, decreased air pollution and improved energy security. Thus, the variation of such consumption between the initial and the final period is explained through the factors of substitution of renewable energy, energy security, energy intensity, carbon productivity, and carbon emission. This is the mechanism for the decomposition in this research. Besides the carbon productivity and energy intensity, other factors could be easily explained as the incentives for renewable energy consumption. As for energy intensity, this paper uses it as a proxy for technology innovation [37] and the orientation of energy structure adjustment [38], which supports the wide application of renewable energy technology. The variable of carbon productivity is likewise used as a proxy for low carbon economic development, as carbon emissions are generally regarded as one driver of renewable deployment [39,40]. There is not a strong and direct substitution between oil import and renewable energy generation in present China. However, future substitution of electricity and bioethanol to oil consumption could be expected because of the fast deployment of new energy vehicles in China. Government policies, incentives and subsidies are very strongly related to the growth of renewable energy consumption, which are merged into the policy orientation of energy security and climate change in this research. Thus, the five components are appropriate for index decomposition analysis.

### 2.3. Grey relational analysis on renewable energy consumption and its components

When firstly introduced by [41], Grey system theory was a useful technique to handle the questions with poor information. It is noteworthy for the wide application of this theory in energy and environment researches [42]. For example, Grey relation analysis was used to examine the influences of residents' consumption of China on the energy use and carbon dioxide emissions and the results revealed that the indirect impacts from lifestyle change were notable for policymaker [43]. Based on the conceptual framework for vulnerability scoping diagram, grey cluster model is applied to research the vulnerability of regional renewable energy systems to climate change in China and to identify the increasing renewable energy vulnerability in the poor areas of China [20]. Next, a brief introduction of grey relational analysis between RE and carbon emission is given as an example.

In this research, $X_i$ ($X_i = (x_i(1), x_i(2), \ldots, x_i(n)),$) is the original renewable energy data series in China, and $n$ represents the time period. The original sequence is normalized by the initial annihilation operator $X_i \times D$, shown as Eq. (8). Thus, the concept $s_i = \int_1^n (X_i - x_i(1))\mathrm{d}t$ could be built for next step.

$$X_i \times D = (x_i(1) \times d, x_i(2) \times d, \ldots, x_i(n) \times d), x_i(k) \times d = x_i(k) - x_i(1), (k = 1, 2, \ldots, n) \quad (8)$$

Provided that the RE consumption data series ($X_i$) and carbon emission data series ($X_j$) of China are depicted as $X_i = (x_i(1), x_i(2), \ldots, x_i(n))$, $X_j = (x_j(1), x_j(2), \ldots, x_j(n))$, which have the initial annihilation image of $X_i \times D$ and $X_j \times D$, namely $X_i^0 = (x_i^0(1), x_i^0(2), \ldots, x_i^0(n))$ and $X_j^0 = (x_j^0(1), x_j^0(2), \ldots, x_j^0(n))$, respectively.

If $s_i - s_j = \int_1^n (X_i^0 - X_j^0)\mathrm{d}t$, $\varepsilon_{ij} = \frac{1 + |s_i| + |s_j|}{1 + |s_i| + |s_j| + |s_i - s_j|}$, the ratio $\varepsilon_{ij}$ can be

named as the absolute degree of grey incidence between renewable energy use and carbon emission for China [20]. The higher grey relational degree indicates the closer relationship between renewable energy consumption and its driver.

This research applies the software GTMS (Grey Theory Modeling Software) 3.0 for calculation. Thus, this study can obtain the grey relational degree between renewable energy development (total renewable energy consumption and new renewable energy consumption) and its decomposition components to analyze their relationships. Also, the results from two types of grey relational analysis can be act as robustness test to gain reliable conclusions.

### 2.4. Scenarios and data sources

Because non-hydro renewable energy statistics in China has been collected in a relatively small scale since 1993 and oil import happened since 1993, this paper focuses on the period of 1993–2011 for the purpose of keeping consistency of statistical caliber. The data of 2012 and 2013 is also collected and employed by LMDI model. The data for oil imports comes from BP [12]. The GDP values are from the website of United Nations Statistics Division.[1] Other data sources are from the World Bank or from calculations based on data of the World Bank. The GDP is measured as 2011 current billion US dollars and other indicators are measured in million tonnes.

Future total renewable energy consumption requirements for the year 2020 and 2030 are estimated for different scenarios. This paper consists of two reference scenarios and a BAU (business as usual) one, which include numbers of economic growth, energy mix, government targets for carbon intensity and total energy consumption. The carbon intensity targets and the proportion of renewables in energy mix are set based on the Twelfth and thirteenth Five Year Plan for Energy Development and U.S.-China Joint Announcement on Climate Change while the projections for energy use and GDP are based on the report of Chinese Academy of Engineering [44]. The oil import is estimated by [45] and [46]. The International Renewable Energy Agency reviewed the renewable potentials and recent trends of renewable energy in China and analyzed the REmap 2030 by reference case and current policy framework [47]. REmap 2030 demonstrated that it is technically and economically feasible to achieve the penetration rate of modern renewables to 26%, which is considered in the scenario analysis depicted as below. GDP and carbon intensity in Table 2 depict the rate of increase or decrease during the period.

In detail, the business as usual scenario depicts China with a gradual economic growth and high oil dependence while the general carbon intensity reduction targets have been reached by Chinese government. 40% reduction in carbon intensity (emissions per yuan of economic activity) by 2020 relative to 2005 level will be delivered in this scenario.

The sustainable development framework demonstrates a pressing concern for coordinated development at national level, including ambitious carbon intensity and energy consumption control targets. A reduction of 45% in carbon intensity is considered for the period of 2005–2020 while the oil import dependency is lower than that of business as usual scenario. The setting of this scenario is close to the policy control or targets launched in the voluntary action of China.

In the renewable energy development case, a more ambitious target is considered for renewable energy penetration. While the total energy consumption of this frame is same to that of business as usual scenario, a more environment-friendly and clean energy system has projected in this frame. The percentage of renewable energy in energy mix will be 25% in 2030, which is higher than the sustainable development scenario and similar to the results from [47]. The carbon intensity reduction targets are same to the sustainable development framework. As a result, the oil import dependence will be reduced at current level (55%) in this case.

[1] http://unstats.un.org/unsd/snaama/dnlList.asp.

## 3. Results and discussion

### 3.1. Positive contribution of energy security to renewable energy development

There is a common agreement in the energy literature, such as in [48,49], which renewable energy generation technology is one of the key energy supply technologies. In China, the concerns about energy structure adjustment, energy security risks, environmental protection and climate change promote the use of renewable energy. Therefore, the energy substitution, energy security, energy intensity, low carbon economy indicator and carbon emission are selected to figure out their contribution to renewable energy development in China.

There is an obvious growth trend in the China's total renewable energy consumption and the number changes from 13.63 million tce in 1993 to 117.85 million tce in 2013, or 8.6 times of the former. Particularly, it can be noticed that total renewable energy consumption experienced a faster pace with an annual average growth of 13.39% since 2000, compared with that of 9.60% during 1993–1999. Table 3 presents the annual contributions of each component to renewable energy consumption. The effects of energy intensity and carbon productivity are relatively stable and humble compared with that of substitution and energy security, with yearly contributions ranging from 1.22 to 31.23 million tce for energy intensity effect, and from 0.99 to 29.49 for carbon productivity effect.

The results also show that the energy security, carbon productivity and carbon emission are positively contributing to the growth of renewable energy consumption. The yearly variation of substitution rate of renewable energy to oil import which is dependent on the oil import and renewable energy use, translates from positive into a negative contribution to renewable expansion. The results for substitution effect reflect the opposite trends between substitution rate and renewable energy consumption. This fact is true for the increasing gap between oil consumption and renewable energy utilization. A subtle change, which occurred in 2013, is the narrow negative effect of substitution rate on renewable energy consumption. The further analysis on this phenomenon need long time series data.

Energy intensity makes a slight negative contribution to the use of renewables, which may demonstrate the renewable market may be policy-oriented or market-driven rather than driven by the promotion of technology in the past two decades. Another reason may be sourced by the origin of energy intensity, such as the role of energy consumption and its structure. As suggested by [25], the main driver of cost reduction in renewable deployment has been market expansion. Thus, the role of technology innovation in renewable energy development requires a further research on cost-effectiveness of renewable energy technology.

### 3.2. Challenges on future requirements for renewable energy transition

To forecast the contributions of the five factors to renewable energy consumption in the future, three scenarios are built in Section 2.5. Table 4 depicts possible paths for future renewable energy development. The contributions of energy intensity, carbon productivity and carbon emission are coincided with the previous decomposition results. It should be noted that because all scenarios have defined the total energy consumption and the growth rate of GDP, the decomposition results for energy intensity would only imply the trends or directions rather than an exact projection. The wide range of possible compositions of the power supply mix shows the challenges of capacity planning with a high renewable penetration rate in China.

The results also present the positive contribution of energy transformation to renewable energy consumption in all scenarios, which

**Table 2**
Scenarios for future social development.

| | BAU | | | Sustainable development | | | RE development | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2015 | 2020 | 2030 | 2015 | 2020 | 2030 |
| GDP | 7.5% | 6.5% | 6% | 7.5% | 6.8% | 6.5% | 7.5% | 6.5% | 6% |
| CI | 17% | 10% | 15% | 17% | 17% | 20% | 17% | 17% | 20% |
| OI | 61% | 65% | 70% | 61% | 65% | 60% | 61% | 65% | 55% |
| RE | 11.4% | 15% | 18% | 11.4% | 15% | 20% | 11.4% | 15% | 25% |
| EC | 41 | 47 | 52 | 41 | 45 | 50 | 41 | 47 | 52 |

Note: CI, OI and EC are the abbreviation of carbon intensity, oil import and energy consumption, respectively.

**Table 3**
Factors annual contributions to renewable energy consumption (Mtoe).

| | $\Delta Re$ | $\Delta SR$ | $\Delta ES$ | $\Delta EI$ | $\Delta CP$ | $\Delta CE$ |
|---|---|---|---|---|---|---|
| 1994 | 4.83 | 2.47 | 1.63 | −1.22 | 0.99 | 0.96 |
| 1995 | 7.30 | −24.15 | 29.45 | −1.86 | 1.43 | 2.43 |
| 1996 | 7.68 | −31.42 | 36.61 | −3.04 | 2.36 | 3.17 |
| 1997 | 8.61 | −43.34 | 49.42 | −4.69 | 3.94 | 3.28 |
| 1998 | 9.80 | −45.23 | 52.31 | −6.07 | 6.19 | 2.60 |
| 1999 | 9.99 | −50.47 | 57.37 | −7.08 | 7.59 | 2.58 |
| 2000 | 12.41 | −55.72 | 63.85 | −8.00 | 9.06 | 3.22 |
| 2001 | 17.70 | −58.55 | 71.04 | −10.11 | 11.24 | 4.08 |
| 2002 | 21.03 | −65.13 | 79.40 | −11.43 | 12.57 | 5.62 |
| 2003 | 25.91 | −72.86 | 88.32 | −11.51 | 10.96 | 11.00 |
| 2004 | 34.31 | −85.97 | 104.77 | −11.74 | 10.66 | 16.59 |
| 2005 | 39.64 | −88.90 | 109.70 | −13.32 | 11.84 | 20.32 |
| 2006 | 44.54 | −95.67 | 117.62 | −15.02 | 13.02 | 24.59 |
| 2007 | 51.91 | −101.80 | 127.63 | −18.80 | 16.51 | 28.37 |
| 2008 | 64.40 | −107.80 | 141.72 | −23.04 | 20.54 | 32.98 |
| 2009 | 70.58 | −113.10 | 148.77 | −24.70 | 21.52 | 38.09 |
| 2010 | 83.77 | −125.10 | 166.41 | −27.28 | 24.71 | 45.03 |
| 2011 | 90.12 | −131.83 | 174.12 | −28.81 | 27.77 | 48.87 |
| 2012 | 91.12 | −159.15 | 192.88 | −29.74 | 26.37 | 60.76 |
| 2013 | 96.92 | −84.22 | 119.62 | −31.23 | 29.49 | 63.26 |

**Table 4**
Forecasts on the contributions of the five factors to the RE consumption.

| | BAU | | | Sustainable development | | | RE development | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2015 | 2020 | 2030 | 2015 | 2020 | 2030 |
| SR | 44.30 | 76.64 | 87.89 | 30.42 | 79.69 | 236.33 | 50.36 | 76.64 | 396.14 |
| ES | 5.13 | 23.08 | 60.19 | 13.12 | 23.99 | −51.44 | −1.44 | 23.08 | −97.62 |
| EI | −29.39 | −64.79 | −391.16 | −62.90 | −92.64 | −337.01 | −66.98 | −64.79 | −281.43 |
| CP | 23.78 | 38.28 | 132.00 | 25.53 | 70.39 | 143.41 | 35.64 | 52.70 | 112.42 |
| CE | 22.37 | 76.13 | 341.27 | 60.02 | 57.41 | 261.31 | 48.61 | 61.72 | 228.09 |

**Table 5**
The relational degrees between renewable energy consumption and its drivers.

| | Total renewable energy consumption | New renewable energy consumption |
|---|---|---|
| SR | 0.6048 | 0.5102 |
| ES | 0.5014 | 0.7644 |
| EI | 0.5069 | 0.7340 |
| CP | 0.5025 | 0.6475 |
| CE | 0.5077 | 0.5000 |

reveals that the desire for transition to renewable energy will be an important incentive to renewable energy development in the next 15 years. Furthermore, the role of energy security will translate into a non-stable contribution to renewable energy use. The reason may be that along with renewable energy development and government's policy related to energy security, the contribution of energy security will gradually drop. Even though this non-stable contribution of energy security may happen, the synergy between energy security and renewable energy development is also embodied in the results. First, the results from Section 3.1 point out the impetus of energy security to renewable energy development. Compared to the business as usual scenario, the renewable energy development scenario in Table 4 reveals renewable energy development will be valued for its contribution to safeguarding energy security. As concluded by [5] that the Egyptian plover is symbiotic to the Nile crocodile, renewable energy could provide golden chances to achieve national energy security strategy.

### 3.3. Relational analysis between renewable energy consumption and its drivers

Based on the method in Section 2.2, the grey relational degrees between renewable energy consumption and the driving forces are listed in Table 5. The new renewable energy consumption is the net additions of renewable energy consumption compared to that of last year, which can help to figure out the timely or the lagging of policy adjustment. The results show that the relations between additional renewable energy consumption and the drivers of ES, EI and CP are closer than that of total renewable energy use.

The results for additional renewable energy consumption suggest that the substitution rate of renewable energy to oil import and carbon emission have more potential to improve their incentives in promoting renewable energy development. This suggestion is also in accordance with the results from the scenarios analyses in Section 3.2, which forecast the increasing important contributions of substitution rate and carbon emission in the future. Energy security ranks first in the relation degree results while energy intensity and carbon productivity follows.

In addition, the results for total renewable energy consumption reveal that in the long run, the total renewable energy consumption only has a tight connection with the substitution rate of renewable energy to oil import. This close relationship is resulted from renewable energy consumption as the numerator of substitution rate.

## 4. Conclusions and policy implications

### 4.1. Conclusions

All societies require energy services for human survival and development. However, energy services must be supplied with low environmental impacts. The combustion of fossil fuels has become an

obstacle to sustainable development in China. While renewable energy has experienced a rapid growth in recent years, the lessons from this development should be further employed. This paper attempts to find out the past pathways to renewable energy development and to forecast these connections between renewable energy consumption and its components by scenarios analysis.

According to the analysis above, the following conclusions could be obtained.

(1) The focus of China's energy policies should still promoting the utilization of renewable technologies. The overview of energy system in China reminds us that even though China is today a global leader in renewable energy deployment, the role of renewable energy could be further explored. Compared to fossil fuel, renewable energy can enhance energy security, create enough jobs and provide options to reduce air pollution and carbon emissions. This is a major incentive for renewable energy deployment in China, as China is the world's largest emitter of $CO_2$ and the largest oil importer.
(2) Energy security, low carbon economy and carbon emission have contributed to the growth in renewable energy consumption in past 20 years. Provided that the energy security situation of China is not optimistic and there is still a long way to go to eradicate the high dependence on oil import, the energy security issues made a bigger effort to renewable energy consumption than carbon productivity and carbon emission. The contributions of energy security, low carbon economy and total carbon emission to renewable energy consumption were 174.12, 27.77 and 48.87 Mtoe, respectively. Furthermore, two factors, energy substitution and energy intensity, did not play a strong role in promoting renewable energy deployment, as their contributions during the period 1994–2011 were actually negative, −131.83 and −28.81 Mtoe, respectively.
(3) Considering the pivotal role of renewable energy in the global transition to a low-carbon future, there exist challenges and barriers during the renewable energy development process in China. Potential opportunities and challenges for China's renewable energy development in the future are forecasted through scenario analysis. This analysis reveals that the positive contribution of energy transformation to renewable energy consumption in the future may occur in all scenarios, such as the projected contribution of 396.14 Mtoe in the renewable energy development scenario. Results from the renewable energy development scenario also suggest that when renewable energy could help to address energy security issues, there will be a slightly negative contribution of energy security to renewables. Furthermore, according to the contribution of carbon emission to renewable energy consumption, the growing environmental challenges make an enlarged role in facilitating the shift towards renewable energy.
(4) There is a complicated feedback mechanism between energy security and renewable energy. The results from index decomposition method and scenario analysis reflect the dual feedbacks between energy security and renewable energy policies, which reveals the synergy between them. This impetus of energy security to renewable energy development is also supported by the closer relationship (0.7644) between energy security and new renewable energy consumption and the weaker connection (0.5014) between energy security and total renewable energy consumption in the grey relational analysis. The outcomes from scenario analysis indicate that renewable energy development will be helpful for safeguarding energy security in renewable energy development scenario. This fact demonstrates that the promotion of renewable energy could be a high priority for China in order to enhance energy supply security.

### 4.2. Policy implications

Based upon the above conclusions, some policy implications for China's renewable energy development are presented as below.

(1) The acceleration in renewable energy development can bring broad benefits, from sustainable development to safeguarding energy security. Even though renewable energy did not have the direct substitution to oil consumption, the big gap between renewable energy utilization and oil import shows that the growth of oil demand is larger than the increase of renewable energy generation, which may result in a negative contribution of substitution effect to renewable energy use. Considering the huge potential of renewable sources, it is wise to promote the renewable energy deployment to meet the huge energy demand in China. However, it is a great challenge for China to reach the balance between short term economic growth and long-term sustainable development [50]. Also, the synergy between energy security and renewable energy policies should be further boosted.
(2) Concern about carbon emissions should be further explored to promote the use of renewables. In turn, renewable energy should be one pivotal and indispensable part in an effort to low-carbon transition. When the past contribution of carbon emission to renewable energy consumption is relatively low, its future role will be enlarged in all scenarios. The popularity of knowledge on climate change and air pollution would be a chance to enhance the public acceptance of renewable energy and its related projects. A stable and sound policy framework for renewable energy development should be built and enacted. Recently, the heavy smog continued to loom in many parts of China, attracting public attention and underlining the transfer from the present coal-based energy system into a more clean energy system. This will offer opportunities for renewable energy development in China.
(3) China can choose a different pathway tailored to the accelerated uptake of renewable energy. The scenario analysis suggests some possible targets for this shift. Also, there are some challenges not mentioned in this study, which include the lower integration rate of emerging renewable generation into energy systems, the need of more attractive policy support in heating and cooling and transport sector as well as the promotion of modern bioenergy application. These challenges could be overcome through effective and overall planning and by optimizing policy mechanisms that value the co-benefits of renewable energy. If the policymakers have decisively spearheaded to facilitate renewable energy in the energy system, it can significantly reduce the environment pollution, safeguard energy security (such as the 55% of oil import in the renewable energy development scenario) and contribute to climate change mitigation.

As China has already been the leader in global renewable energy industry, it is the time for China to harness and nurture a diverse range of renewable technologies. The reasons for renewable energy development are a combination of socio-economic and energy policies, the economic viability of renewable technologies. Based on a general introduction about the energy system in China, this paper adopts an index decomposition method to research the historical path for renewable energy consumption and connects renewable energy utilization to energy system transformation, economic development and carbon emissions. Scenarios analysis offers some important implications for future renewable energy development. Two kinds of grey relation analysis provide the long-term and timely connections between renewable energy consumption and its components.

However, the improvements for this study are also suggested. As suggested by [47], renewable energy technologies could offer the cost-competitive options for delivery of modern energy services in remote areas, while innovation and scale merit continue to achieve cost savings. This paper did not consider the economic viability and competitiveness of renewable technologies [51], the cooperation in renewable energy development [52] in promoting the use of renewables. Other factors should be further explored [53,54]. Furthermore, the LMDI

method is not effective in examining the considerable time lags and the dynamic mechanisms between renewable energy policy enactment and its impacts and SDA may be a good choice [55]. With availability of expanded data resources, the structure of renewable energy system, as well as the system dynamics approach could be included in further research.

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